The development of shear strain in undrained multi-directional simple shear tests

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ABSTRACT: Actual earthquakes apply horizontal shear forces on soil in a multi-directional manner. The effects of multi-directional seismic loading on the undrained behaviour of medium dense Hostun sand was recently studied with stress-controlled undrained cyclic multi-directional simple shear tests. The development of shear strain in several tests with uni-directional, oval and circular loading paths is compared and the preliminary results are reported here. The general geometry of the strain paths resembles that of the loading paths. But strain paths are diverted when excess pore pressure ratio exceeds a certain threshold (0.6-0.7 in this study). The existence of static shear stresses further complicates the development of shear strain. Downhill shear strain happens no matter what direction the cyclic shearing is applied in. The shear strain in the perpendicular direction is limited if the static shear stress is large enough to eliminate stress reversal. The knowledge regarding the development of shear strain in multi-directional loading conditions remains scarce and more efforts are needed to advance the understanding of this topic.

1 INTRODUCTION

The undrained response of sand to cyclic shearing has been extensively investigated in the field of geotechnical engineering. The simple shear test is one of the preferable element-level laboratory tests to study the topic as it reproduces in situ loading conditions in a reasonable way and allows continuous rotation of principal stresses. However, most of the existing simple shear apparatuses shear soil specimens only along a single horizontal direction, whereas actual earthquakes apply horizontal shear in a multi-directional manner.

Since Pyke et al. (1975) reported gyratory loading paths induced higher settlement of sand in shake table tests than uni-directional loading paths, efforts have been made towards developing multi-directional simple shear devices and advancing the understanding of multi-directional loading. A limited number of multi-directional simple shear tests have been conducted on sand (Casagrande and Rendon, 1978; Ishihara and Yamazaki, 1980; Ishihara and Nagase, 1988; Fukutake and Matsuoka, 1989; Clough et al., 1989; Boulanger and Seed, 1995; Meneses et al., 1998; Kammerer, 2002; Chen et al., 2004; Matsuda et al., 2004; Sako and Adachi, 2004; Duku et al., 2007; Jin et al., 2008; Sivathayalan and Ha, 2011; Li et al., 2016)

The undrained soil behaviour in multi-directional simple shear tests differ remarkably from uni-directional tests in various aspects, with the development of shear strain being no exception. Shear strain induced by multi-directional loading accumulates in a multi-directional manner. This poses a challenge to existing models for geotechnical deformation prediction since many of them were developed based on uni-directional tests and have not been validated for multi-directional conditions.

Considering the scarcity of testing data, the development of multi-directional shear strain is far from being fully understood and requires more investigation. This paper presents some of the preliminary results obtained from a recent experimental study.

2 UNDRAINED MULTI-DIRECTIONAL SIMPLE SHEAR TESTS

The sand tested in this study was Hostun Sand, which has e_{max} of 1.01, e_{min} of 0.555 and specific gravity at 2.65. The particle size distribution curve is shown in Figure 1, with D_{50} at 0.35 mm. Reconstituted samples were prepared with the air-pluviation method and all had a diameter-to-height ratio over 3.75 to minimise the effects of the lack of complementary stresses, following Franke et al. (1979). Carbon dioxide percolation was carried out before samples were installed to achieve good saturation. Post-consolidation relative density was used to represent the density of the samples.

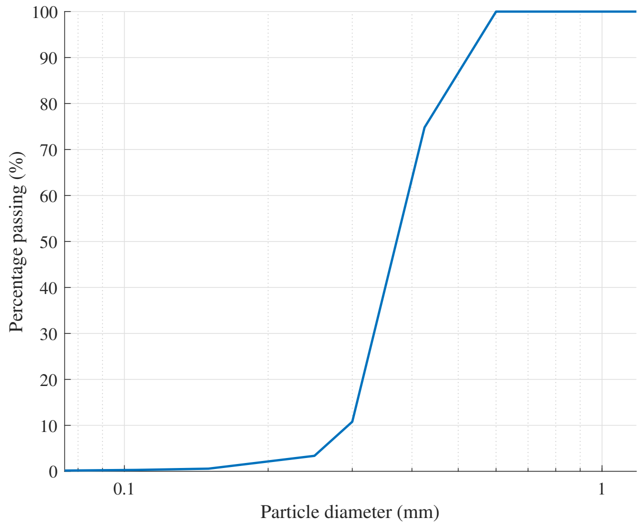


Figure 1. Particle size distribution curve for Hostun Sand.

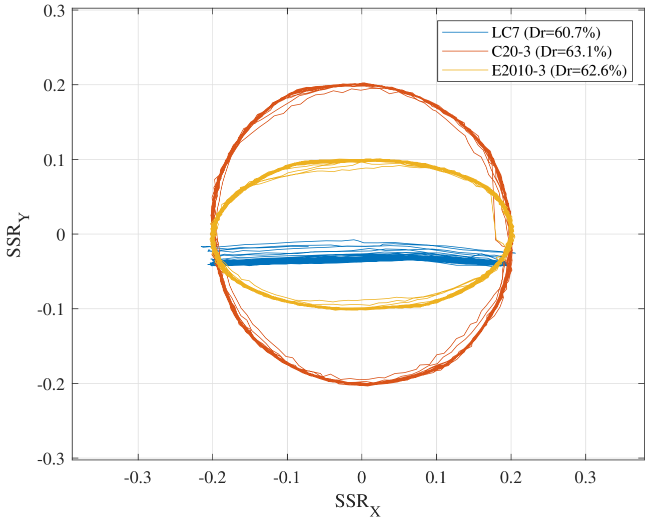
The multi-directional simple shear apparatus developed by Rutherford and Biscontin (2013) was used for the experimental program in this study. The testing device features a chamber that allows the application of cell pressure and two perpendicular horizontal actuators that can apply multi-directional shearing on the horizontal plane. The soil samples are confined by a stack of lubricated steel rings. The specifications of the testing system can be found in Rutherford and Biscontin (2013).

The results of several tests, with uni-directional, circular and oval loading paths, will be shown here. The testing information for these tests is summarised in Table 1. The plan view of the loading paths is presented in Figure 2(a) and 6(a).

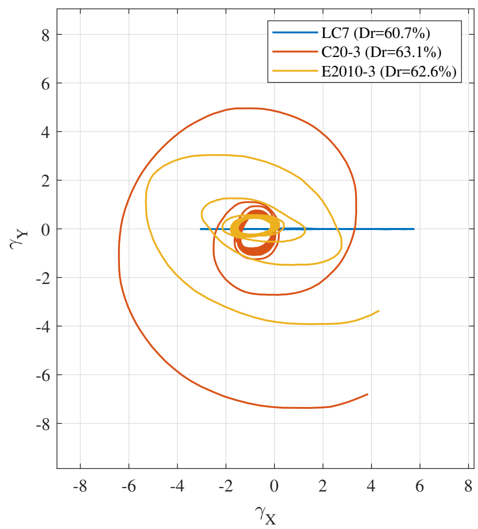
Table 1. Summary of the tests

Test name	Test type	D_r (%)	B-value	N_L	$\sigma'_{v,i}$ (kPa)	SSR_X	CSR_X	SSR_Y	CSR_Y
LC7	Linear	60.7	0.97	62	100	0	0.197	0	0
C15-2	Circular	57	0.88	58	100	0	0.154	0	0.151
C20-3	Circular	63.1	0.96	19	100	0	0.201	0	0.201
C15-X7.5-1	Circular	55.4	0.90	33	100	0.072	0.152	0	0.153
C15-X15-1	Circular	56.4	0.97	89	100	0.147	0.152	0	0.150
E2010-3	Oval	62.6	0.94	60	100	0	0.202	0	0.100

*N_L is the number of cycles to liquefaction. SSR_X and SSR_Y represent the initial static shear stress ratios in X and Y direction. CSR_X and CSR_Y are the amplitude of cyclic shear stress ratios in X and Y direction.



(a) Plan view of shear stress ratio



(b) Plan view of shear strain

Figure 2. Comparison of uni-directional linear, oval and circular tests with the maximum cyclic shear stress ratio at at 0.2, with the plan-view of shear stress ratio plotted in (a) and shear strain in (b)

3 TEST RESULTS

Figure 2 compares the plan-view shear stress and strain of uni-directional linear test LC-7, oval test E2010-3 and circular test C20-3 (loading proceeds in anti-clockwise direction). The maximum cyclic shear stress ratios of the three tests are the same at 0.2, with the primary shear directions aligned in the X direction, as shown in Figure 2(a). Clearly, the strain paths of these tests reflect the geometrical features of their loading counterparts. The shear strain accumulates in a circular way in a spiral pattern. By contrast, the uni-directional test has minimal shear stress in Y direction and thus has only marginal shear strain in that direction.

The primary direction of the shear strain development in the oval test E2010-3 is generally in accordance with the orientation of the major axis of its elliptical loading path. However, it is noted that the strain path of the test exhibits rotation that is not seen explicitly in the uni-directional and circular tests. The strain path of E2010-3 tends to rotate when large shear strain develops and liquefaction is imminent.

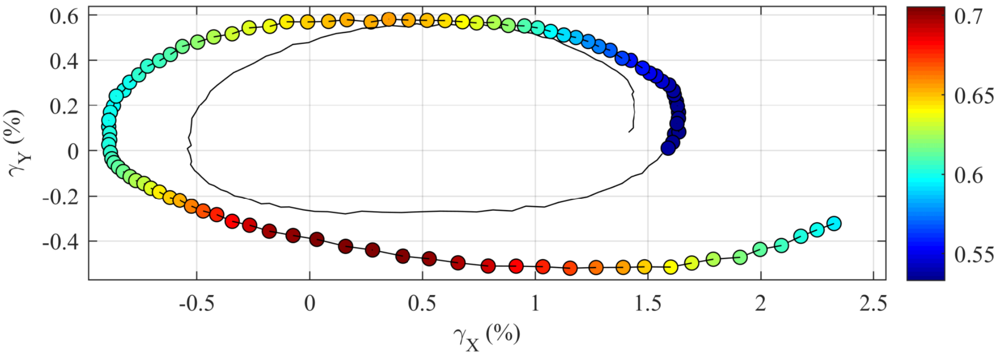


Figure 3. The strain path of the 58th cycle of oval test E2010-3, with excess pore pressure ratio indicated by colour. (The 57th cycle is also included, without showing for excess pore pressure ratio.)

Figure 3 presents the plan-view shear strain of the cycle of oval test E2010-3, where the strain path of the test starts to rotate considerably, as seen in Figure 2. Excess pore pressure ratio is indicated by the colour of the data points. The 57th cycle is also included as a reference, without showing for excess pore pressure ratio, though. The shear strain in the first half of the 58th cycle accumulates along a similar oval route to the elliptical loading path, but dramatic deviation takes place subsequently. The most distinct development of shear strain occurs when excess pore pressure ratio exceeds 0.65, reflected by the increasing distance between neighbouring data points.

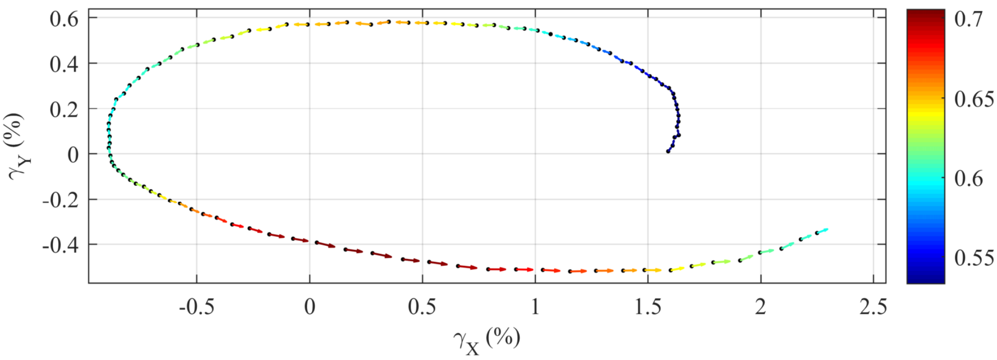


Figure 4. The strain increment vectors of the 58th cycle of oval test E2010-3, with excess pore pressure indicated by colour. (The start points of the vectors are marked by dark dots.)

The close connection between strain increment and excess pore pressure ratio can also be found in Figure 4, where strain increment vectors are plotted. The length of the vectors is proportional to their magnitude and the colour indicates excess pore pressure ratio. Short strain increment vectors are seen in the section where excess pore pressure is relatively low, while the longest strain increment vectors appear where excess pore pressure exceeds 0.65. Significant strain accumulates towards the direction of those long strain increment vectors, while less strain develops in the direction of short ones. As a result, the development of the strain path is diverted, causing rotation.

The relationship between the magnitude of shear strain increment versus excess pore pressure ratio is presented in figure 5 for all the sample tests (dark open circles), with test E2010-3 in red solid circles. Despite scatter, it appears that an excess pore pressure threshold exists, below which the corresponding strain increment is small but after which strain increment soars. For test E2010-3, this threshold is around 0.65, while it ranges from 0.6 to 0.7 across the other tests. This suggests the softening of sand, in undrained loading conditions, becomes prominent when excess pore pressure ratio reaches a threshold. Measures should be taken in practice to avert this threshold to avoid detrimental deformations.

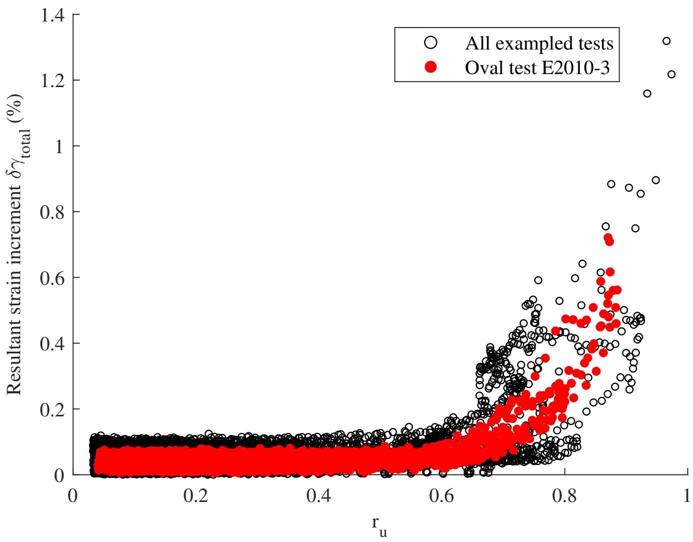
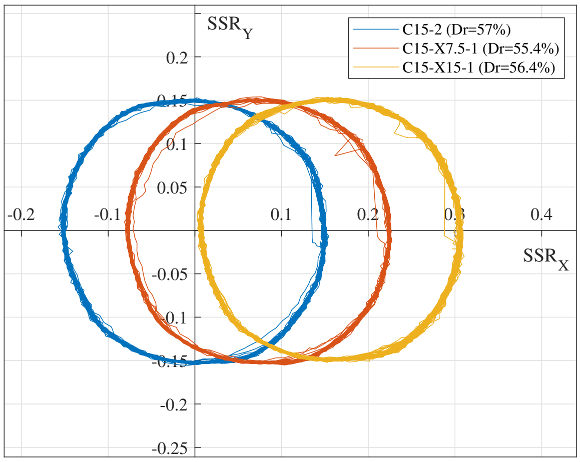


Figure 5. The magnitude of strain increment versus excess pore pressure ratio for all the shown tests.

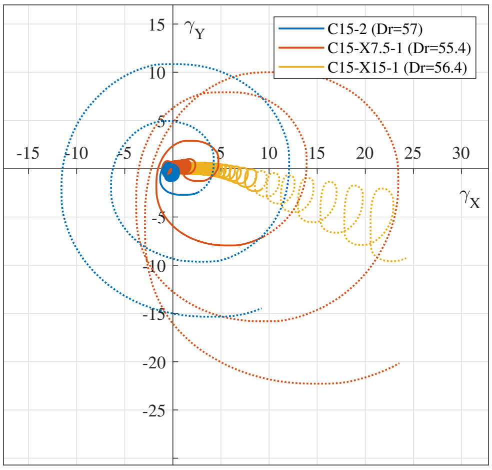
The pattern of shear strain development is further complicated if a constant static shear stress is introduced. Figure 6 compares three circular tests with different static shearing. The shear strain of post-liquefaction cycles is also included with dotted curves. Test C15-2 has no static shear stress and thus has a spiral strain path. Test C15-X15-1, on the contrary, has the largest static shear stress that eliminates stress reversal in the X direction. Shear strain in this test accumulates primarily along the X direction with only marginal strain developing in the Y direction ($\gamma_Y = 2.5\%$ when $\gamma_X = 10\%$). Having moderate static shearing, by contrast, test C15-X7.5-1 develops a strain path with off-centred spiral geometry that combines the features of the other two tests.

There is a clear tendency of shear strain to accumulate towards the direction of static shearing. A similar observation has been reported for both sand and clay (Kammerer, 2002; Biscontin et al., 2004; Rutherford, 2012). This implies that downhill deformation (landslide) can take place in sloping ground no matter what direction the cyclic shearing is in. The seismic safety of structures and infrastructure constructed on sloping ground cannot be taken for granted even if the slope is small, especially when serviceability is crucial.

Furthermore, when static shearing is large enough to eliminate stress reversal in the downhill direction, such as in test C15-X15-1 where SSR_X is always positive, the strain potential in the perpendicular direction is limited counter-intuitively. Post-liquefaction shear strain increases rapidly in both dip (X) and strike (Y) direction in test C15-2 and C15-X7.5-1. By contrast, the shear strain in test C15-X15-1 accumulates much faster in the dip direction (X) than in the strike direction (Y). Kammerer (2002) suggested this phenomenon is a result of reduced stress rotation. Full rotation of stress vector does not occur when stress reversal is inhibited in a direction, resulting in limited development of strain in test C15-X15-1. Evidently, the specific geometry of a



(a) Plan view of shear stress ratio



(b) Plan view of shear strain

Figure 6. Comparison of three circular tests with different initial static shearing, with the plan-view of shear stress ratio plotted in (a) and shear strain in (b)

loading path exerts influence over the development of shear strain, which should not be overlooked by earthquake geotechnical research and practice.

4 CONCLUSIONS

While the testing data regarding the development of shear strain in multi-directional loading conditions remains scarce, a recent experimental study was conducted to contribute to this topic. Undrained cyclic multi-directional simple shear tests were performed on medium-dense Hostun sand. The results of several tests were shown and analysed. The preliminary findings regarding the development of shear strain include:

1. The general geometry of the strain paths resembles that of loading paths. Strain paths are diverted, depending on the specific loading path, when excess pore pressure exceeds a certain threshold.
2. An excess pore pressure ratio threshold is found to separate the phase of limited strain accumulation from that of runaway strain development. The excess pore pressure ratio threshold ranges from 0.6 to 0.7 for the tests in this study.
3. The existence of static shearing further complicates the development of shear strain. Downhill accumulation of shear strain happens no matter what direction cyclic shearing is applied in. Large static shear stresses that eliminate stress reversals can reduce the development of shear strain in the perpendicular direction.

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